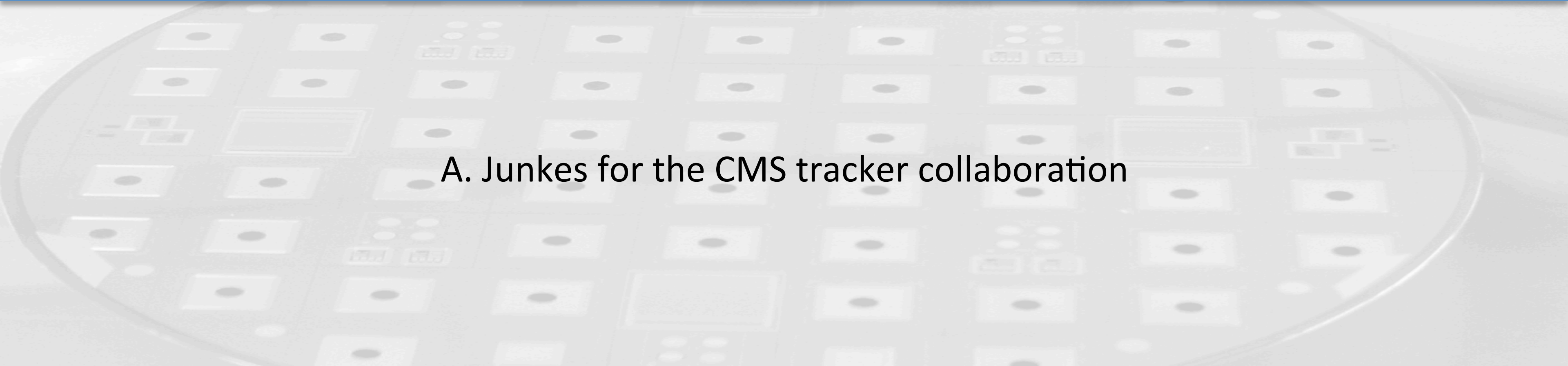
# Energy Dependence of Proton Radiation Damage in Si-Sensors



A. Junkes for the CMS tracker collaboration

November 19th 2014
25th RD50 meeting
CERN

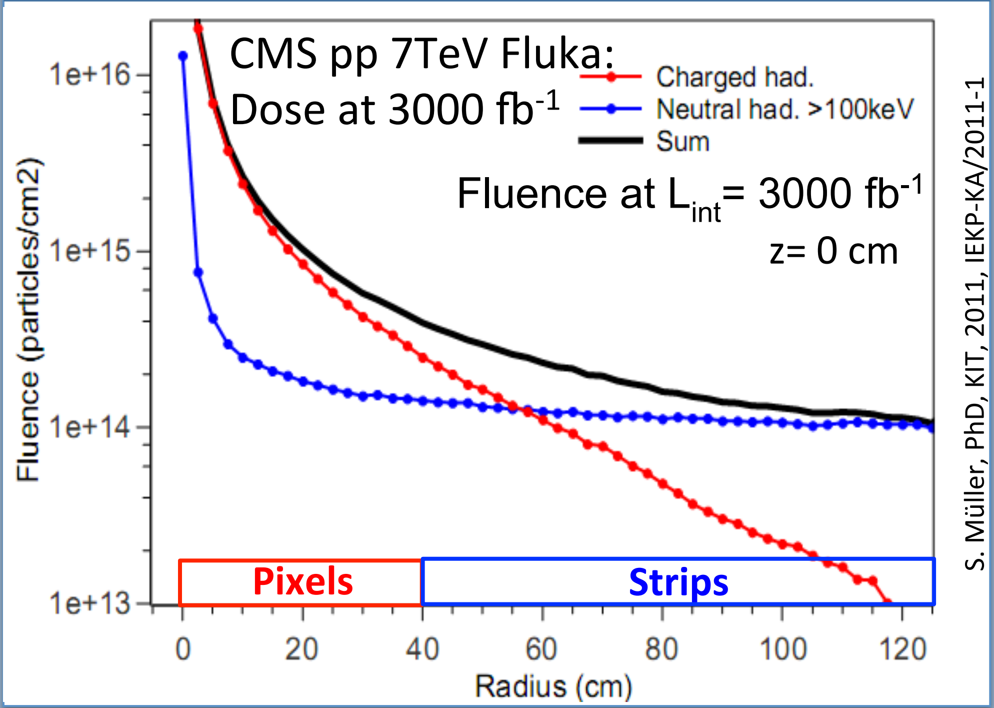
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

CMS
Compact Muon Solenoid

# Motivation

Expected fluence for the CMS tracker



S. Müller, PhD, KIT, 2011, IEKP-KA/2011-1

Radiation levels of fluences up to $\Phi = 10^{16}$ cm$^{-2}$ are expected for CMS

Radiation damage changes the performance of the sensors

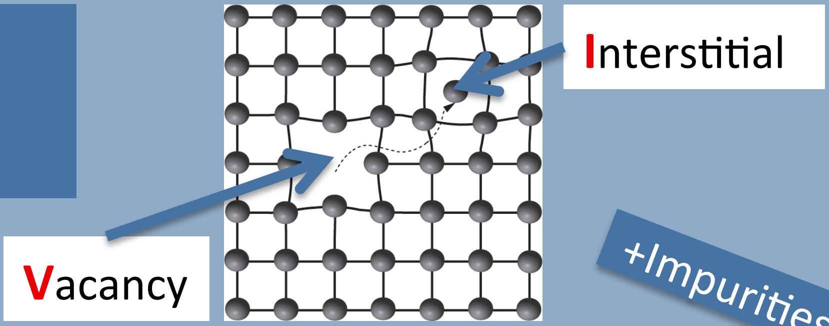
- Increase of leakage current
- Increase of trapping
- Change of the depletion voltage

Understanding of radiation damage is important for the design of the sensor

This presentation focuses on defects responsible for the change of the depletion voltage

# Point and cluster defects

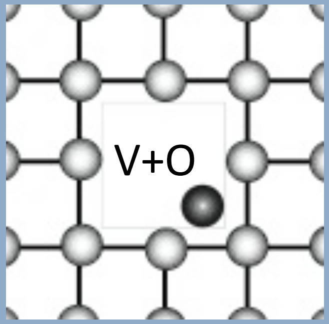
Primary knock-on-atom creates vacancies and interstitials



**I**nterstitial

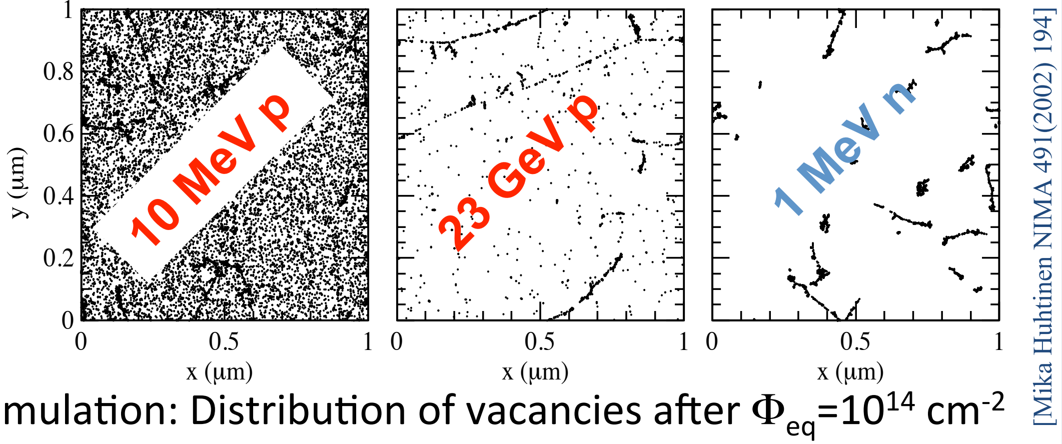
**V**acancy

+Impurities



Couple with impurities to defect complexes

## Depending on particle type and energy



[Mika Huhtinen NIMA 491(2002) 194]

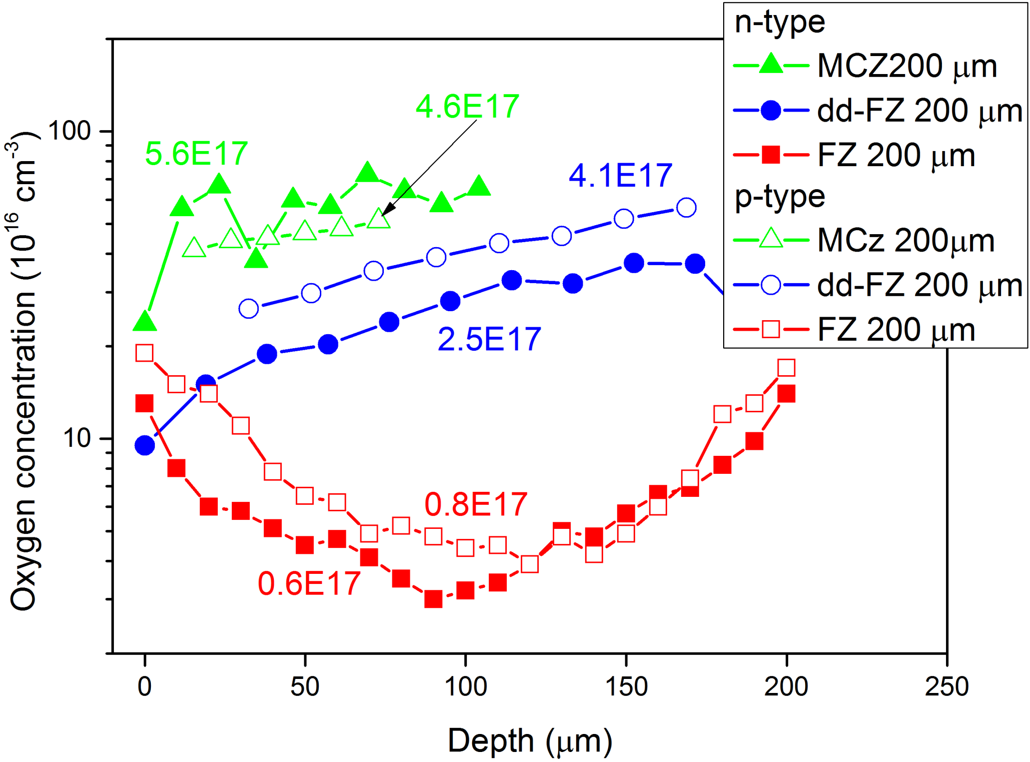
Simulation: Distribution of vacancies after $\Phi_{eq}=10^{14}$ cm$^{-2}$

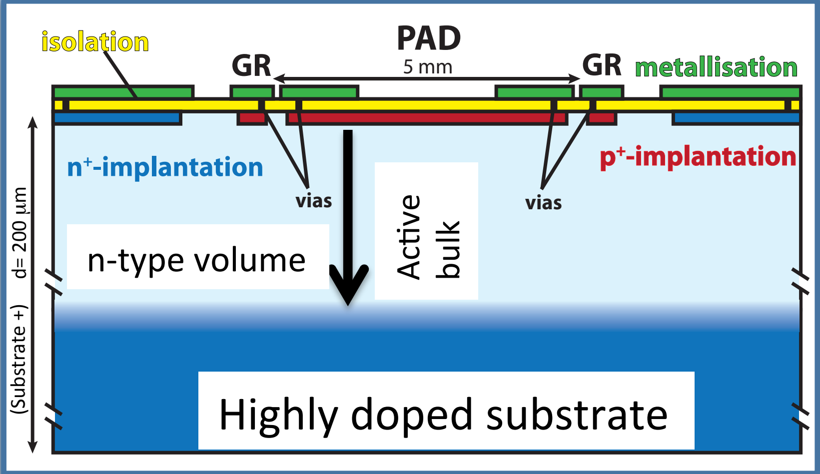
Proton irradiations in this study: 23 MeV, 23 GeV, 800 MeV

Change of detector properties as result of defect generation
→ Aim: Understanding of microscopic defects depending on irradiation type

# Materials

## Oxygen profiles (SIMS measurements)



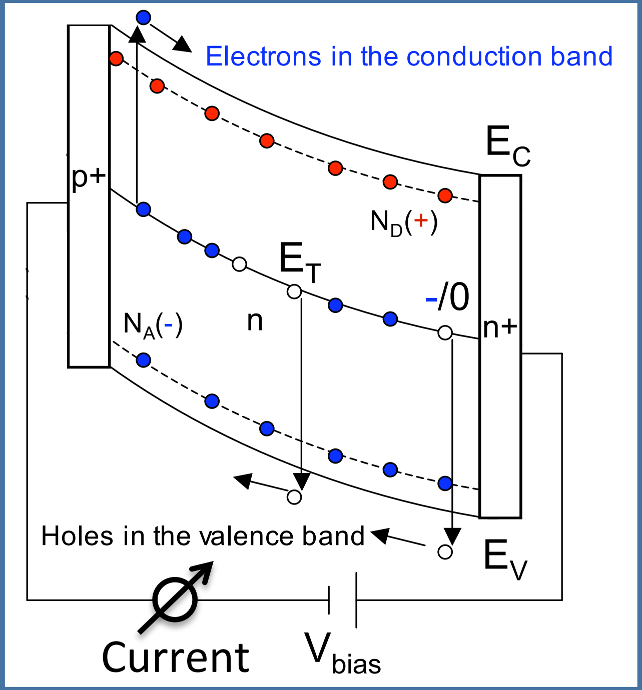


Oxygen profiles are not homogeneous
→ Take average

N- and P-type pad-diodes from the “CMS-HPK” campaign
Deep-diffused Float Zone (dd-FZ), 200 μm (200 μm active bulk + 120 μm substrate)
Float Zone (FZ), 200 μm
Magnetic Czochralski (MCZ), 200 μm

# Thermally Stimulated Current technique

## TSC principle



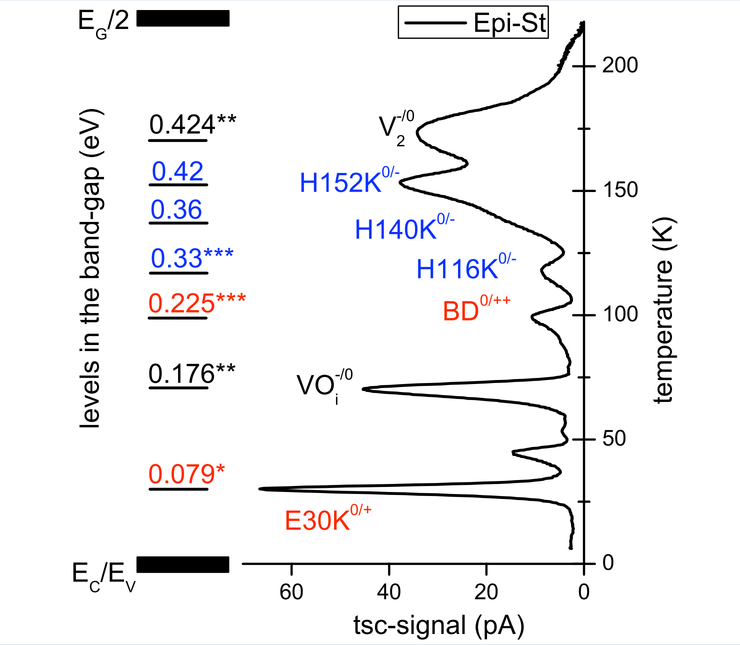
*Single shot* technique:

1. Filling of traps with charge carriers at low T (<30 K)

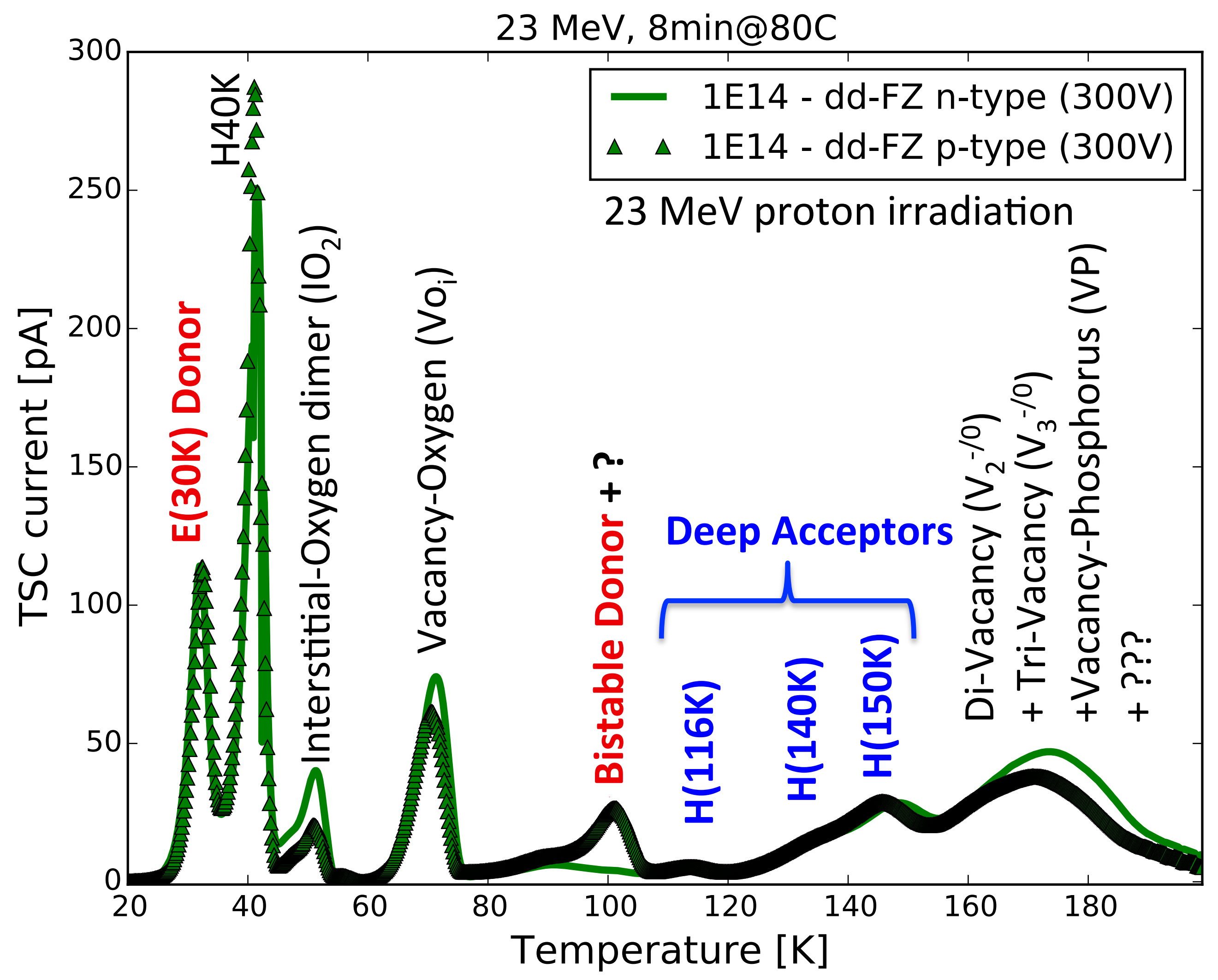
→Filling (majority carriers with zero bias, majority and minority carriers by forward bias, light)

2. Recording of charge emission ($e_{e,h}$) from filled traps during constant heating
3. $N_D$ from integral of TSC-current

- Signal as function of temperature



# Comparison of n- and p-type sensors



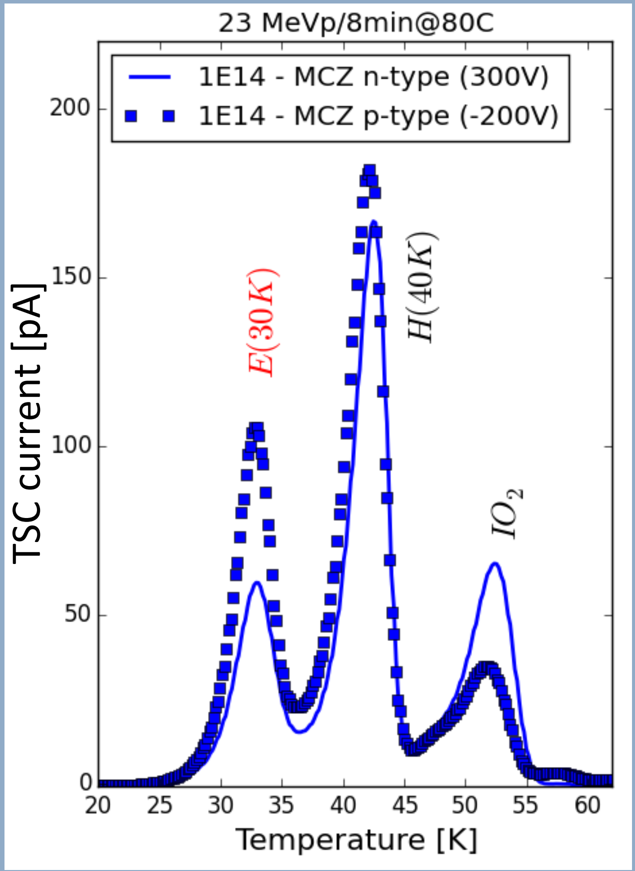
23 MeV p irradiation
Deep-diffused FZ

- Introduction of main defects similar in n- and p-type material
- Slight difference on single defects

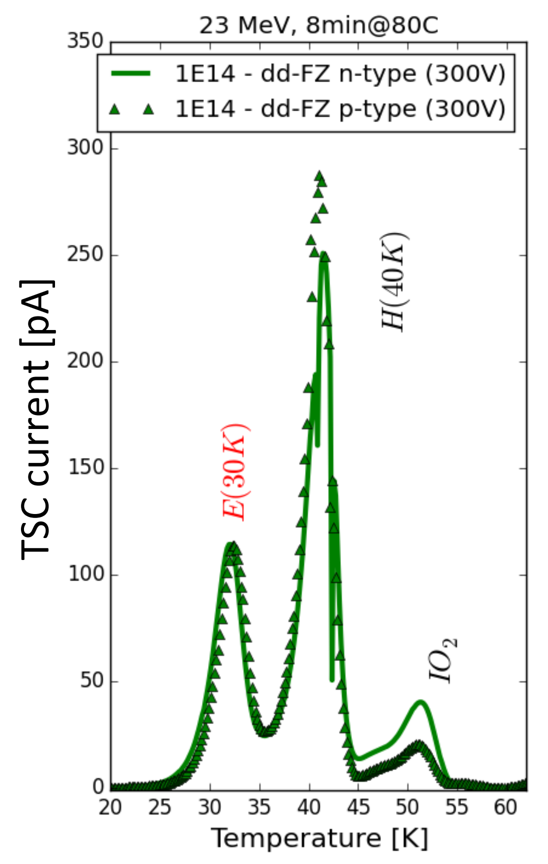
$$\text{Introduction rate} = \frac{\text{Defect concentration}}{\Phi_{eq}}$$

# Oxygen dependence of E(30K)

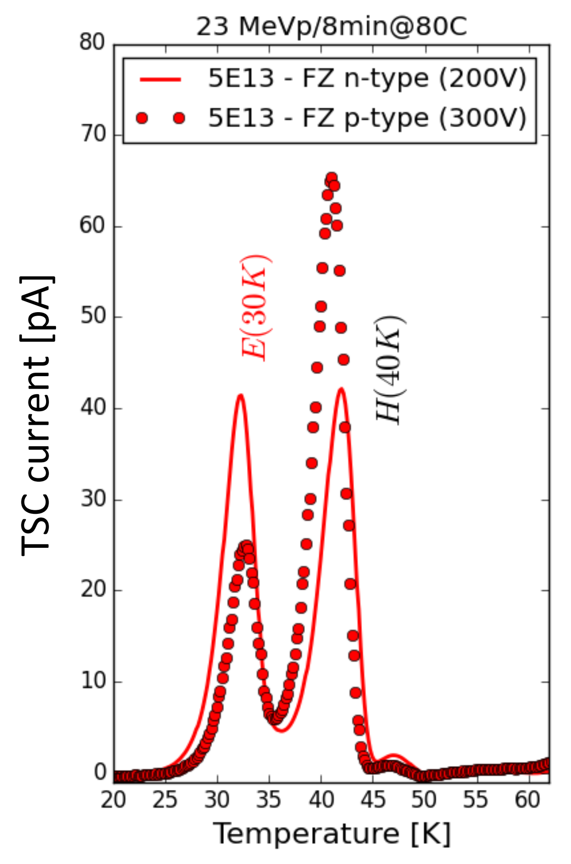
MCZ (high [O])



dd-FZ (medium [O])



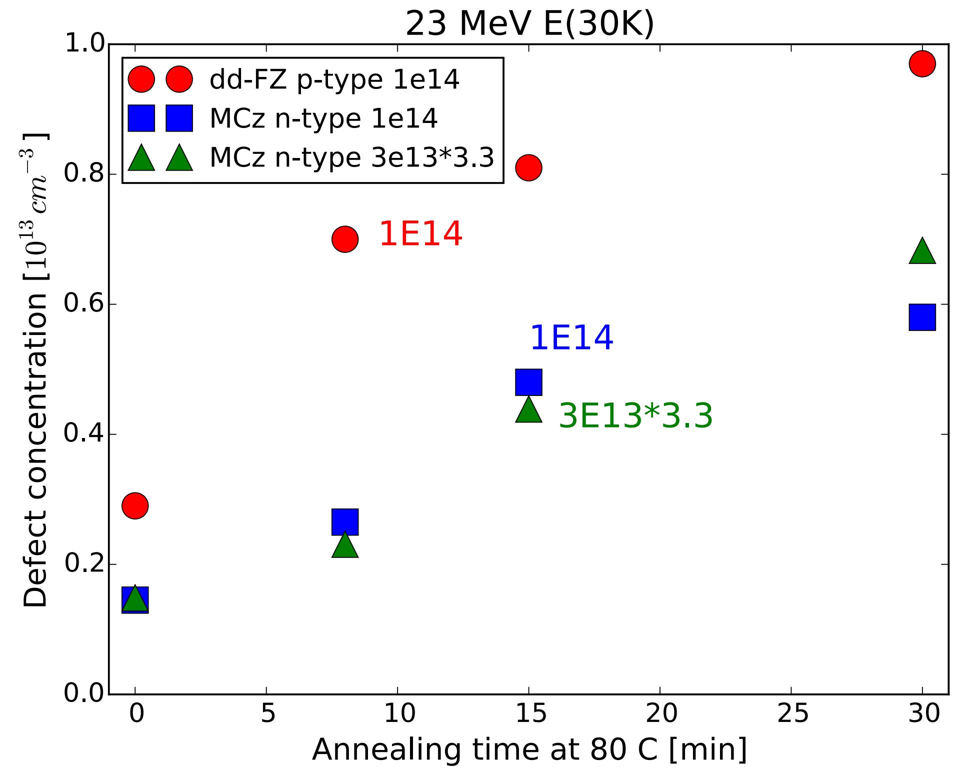
FZ (low [O])



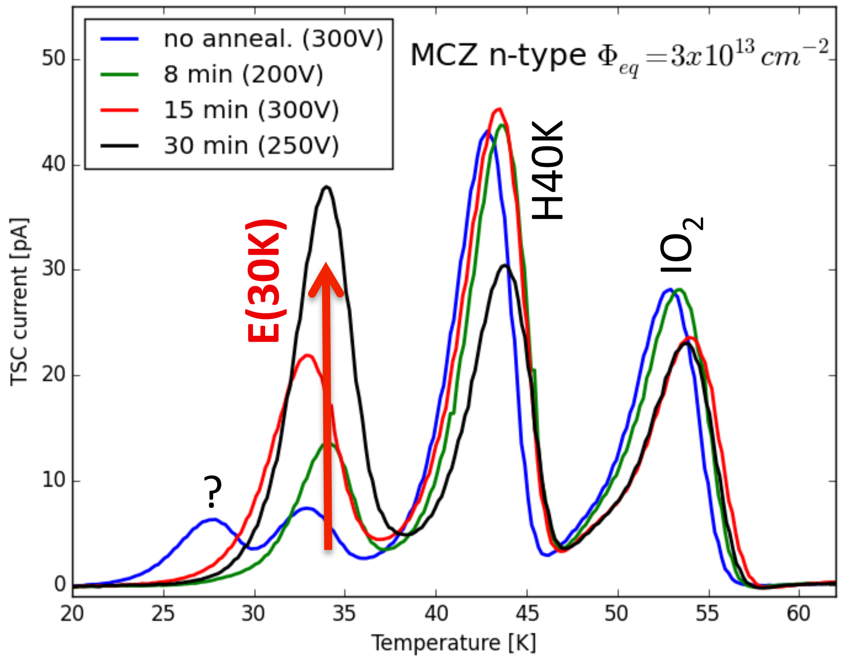
P-type: Introduction rate of E(30K) increase with oxygen concentration
N-type: Introduction rate of E(30K) decrease with oxygen concentration

# Annealing behavior of donor E(30K)

## Annealing behavior of E(30K)



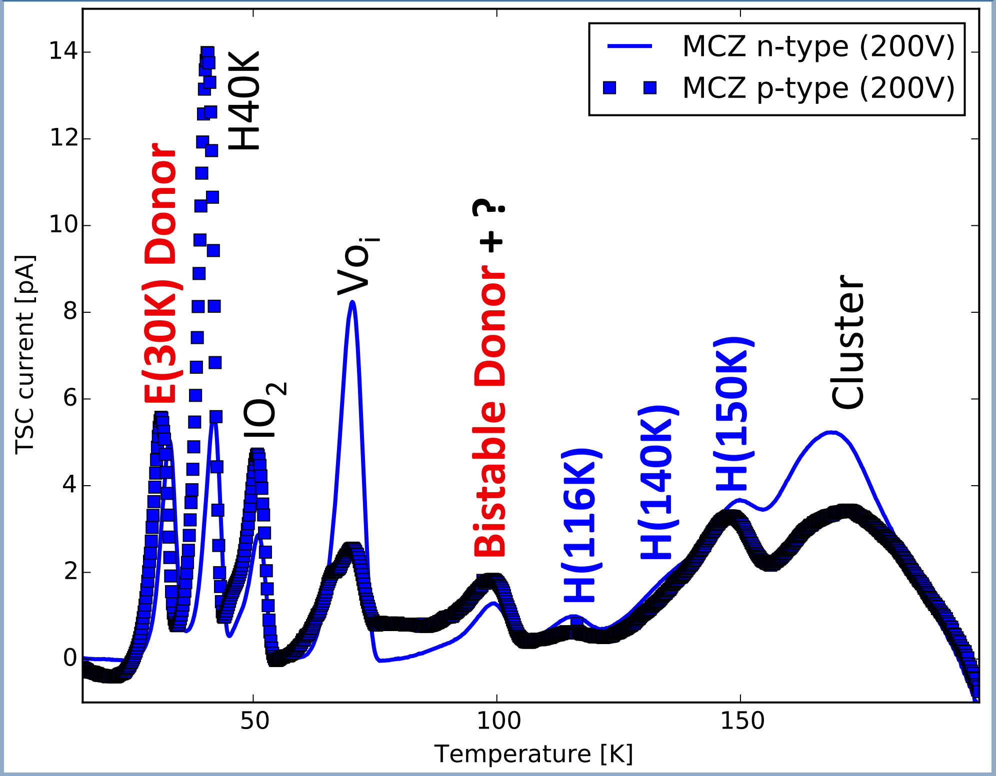
## TSC Spectra during 80 C annealing



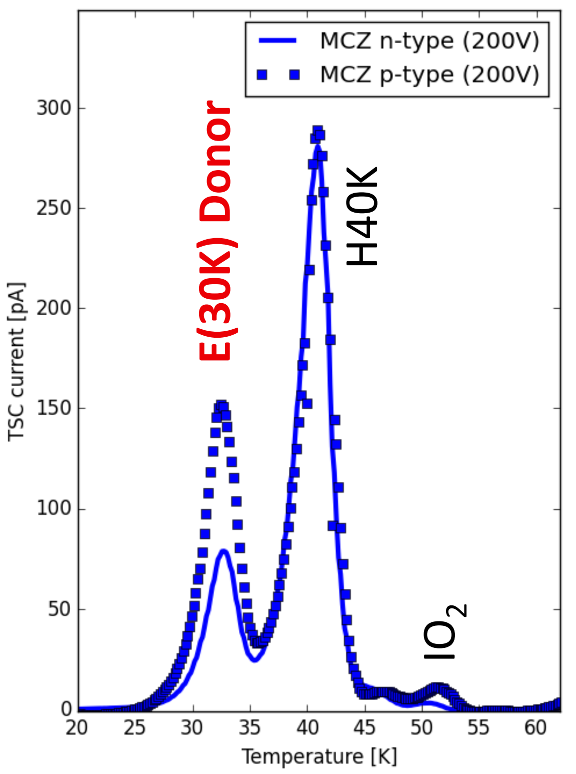
Time dependence of annealing of E(30K) very similar for different materials
Introduction rates for E(30K) for MCz similar for different fluences

# High Energy Proton Irradiated Sensors

MCZ: $\Phi=1\times10^{13}$ cm$^{-2}$



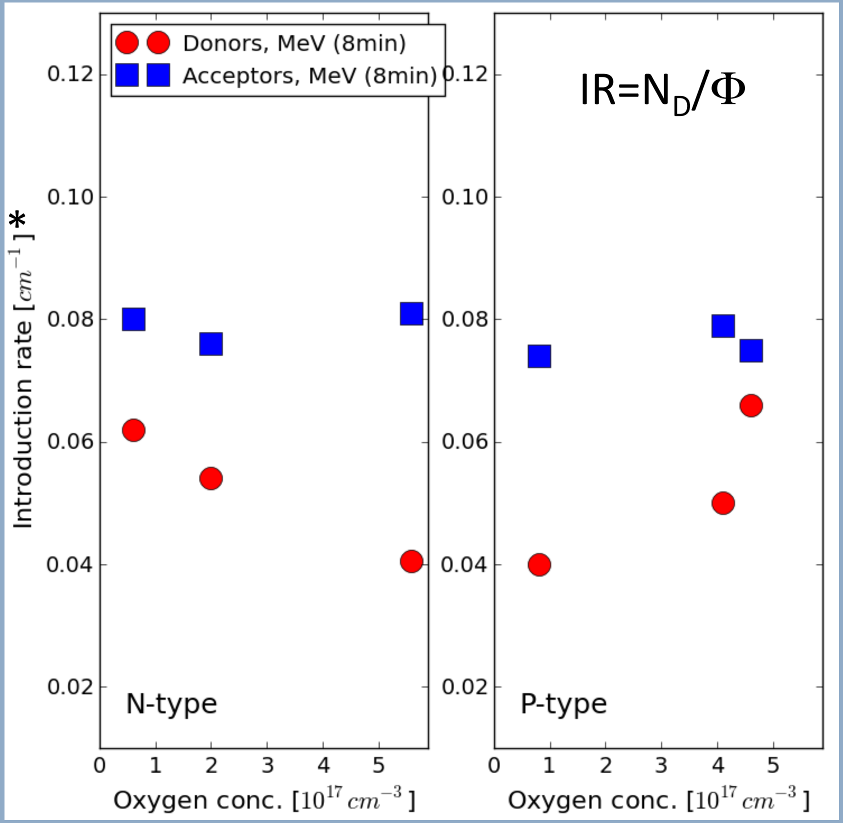
MCZ: $\Phi=3\times10^{14}$ cm$^{-2}$



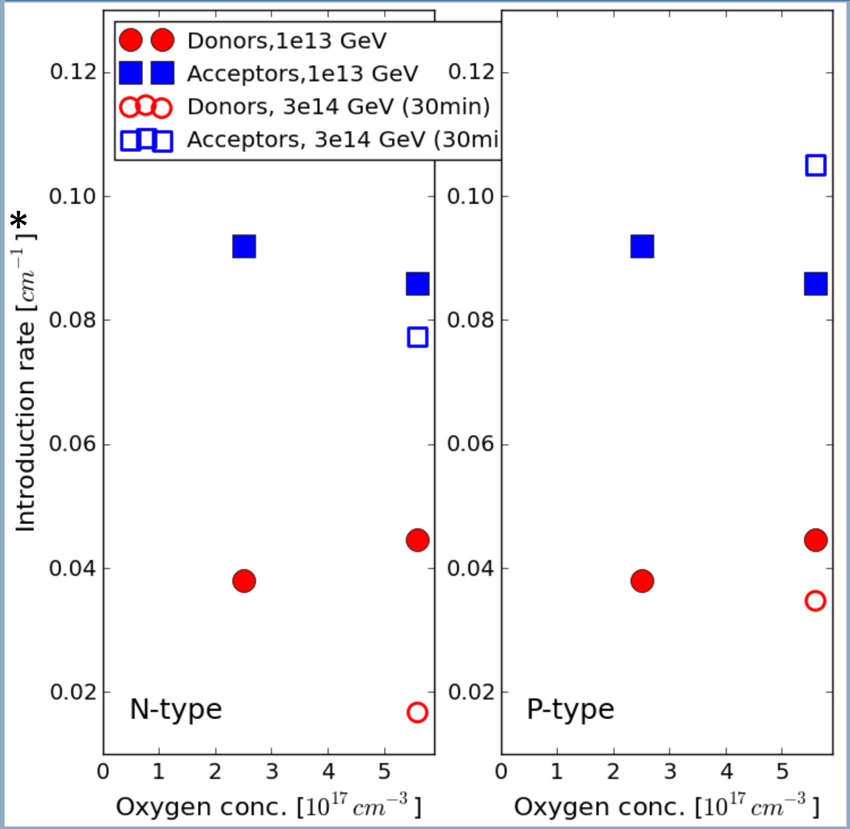
- Point defects (like $IO_2$) suppressed after 23 GeV proton irradiation
- Effect large at high fluences → Filling of defects suppressed
- Possible reason: shielding from cluster defects

# Comparison of introduction rates

## 23 MeV protons



## 23 GeV protons



*IR used in V.Eremins's defect model about two orders of magnitude higher

23 MeV protons
- Generation rate constant for acceptors
- Oxygen dependence for donors

23 GeV protons
- Generation of acceptors compatible
- Generation of donors reduced

# Summary

23 MeV protons

- Defect generation in p-type silicon very similar to n-type silicon
- Oxygen dependent donor generation observed
- Similar generation of acceptors

→ General understanding of radiation damage true for p-type

23 GeV protons

- TSC measurement technique problematic
- Point defect signature suppressed
- Effect more dominant for high irradiation fluences
- Possible explanation: Shielding of point defects from cluster defects

Outlook

Try other filling methods for GeV p irradiated samples (light)

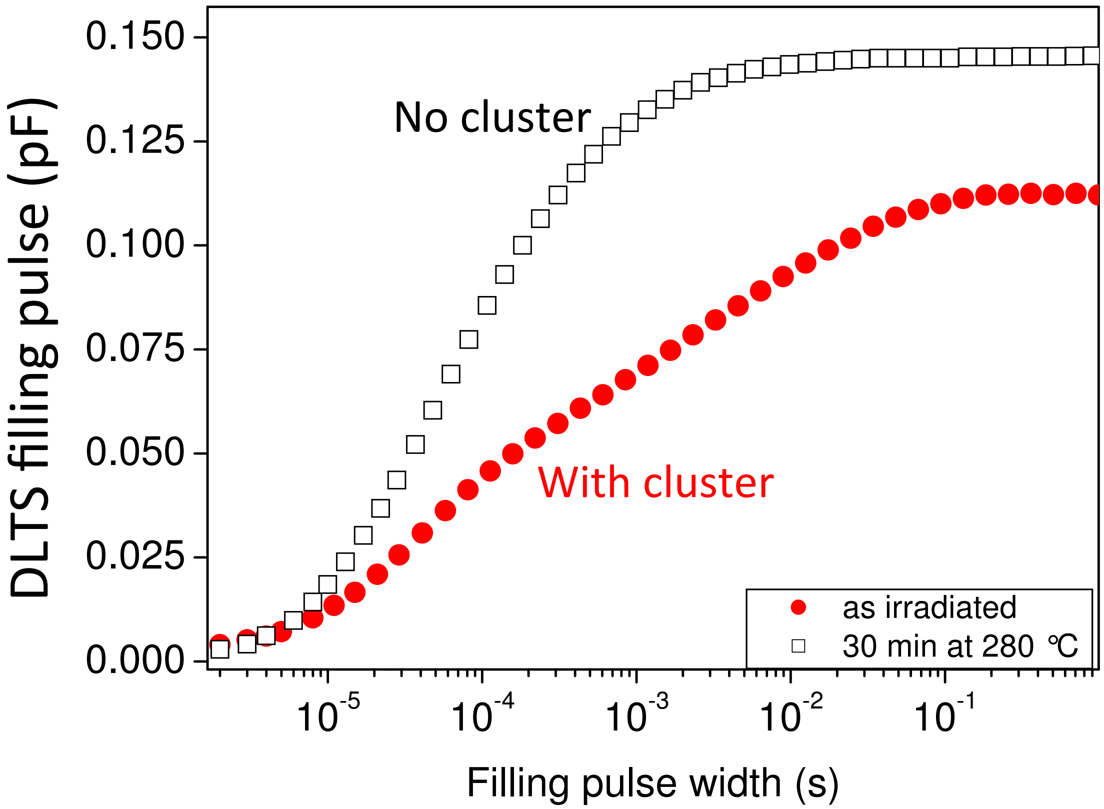
Exploit effect of shielding from clusters from DLTS investigations

Investigate pion and 800 MeV irradiated samples

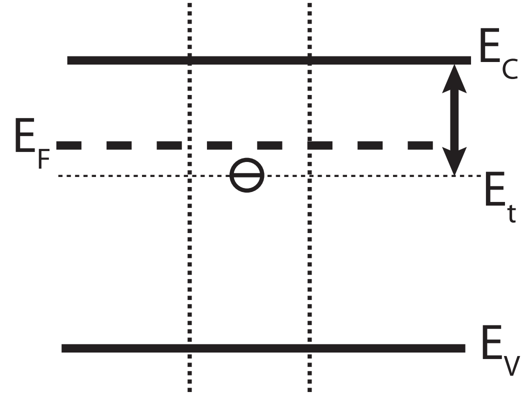
# Back Up

# Clustering effect

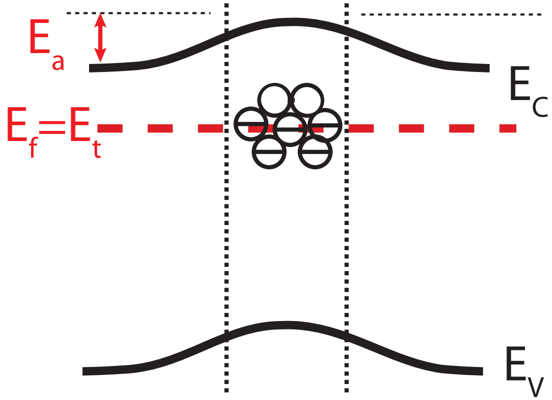
## Capture cross section measurement of $V_2^{=/-}$ in FZ



## Point defect



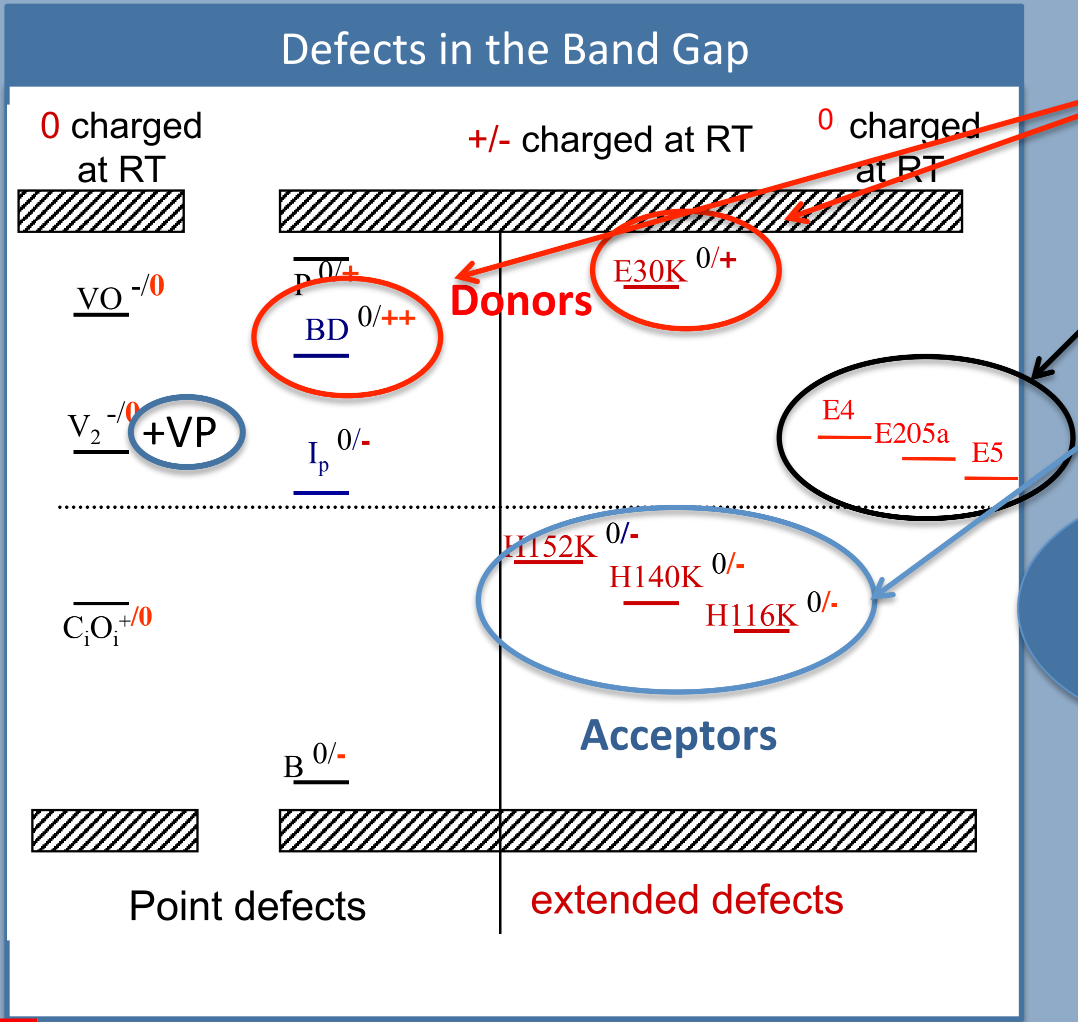
## Cluster influence



A. Junkes

# Understand correlation between microscopic and macroscopic effects

Defects in the Band Gap



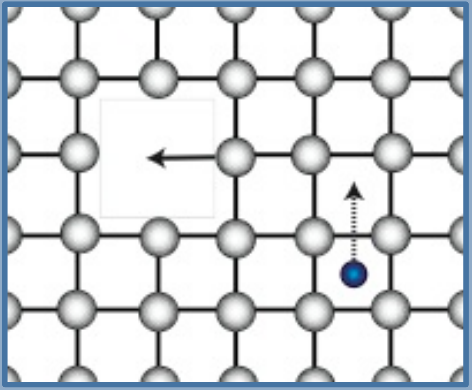
Positive space charge

Leakage current

Negative space charge

What am I doing here?

# Oxygen rich silicon



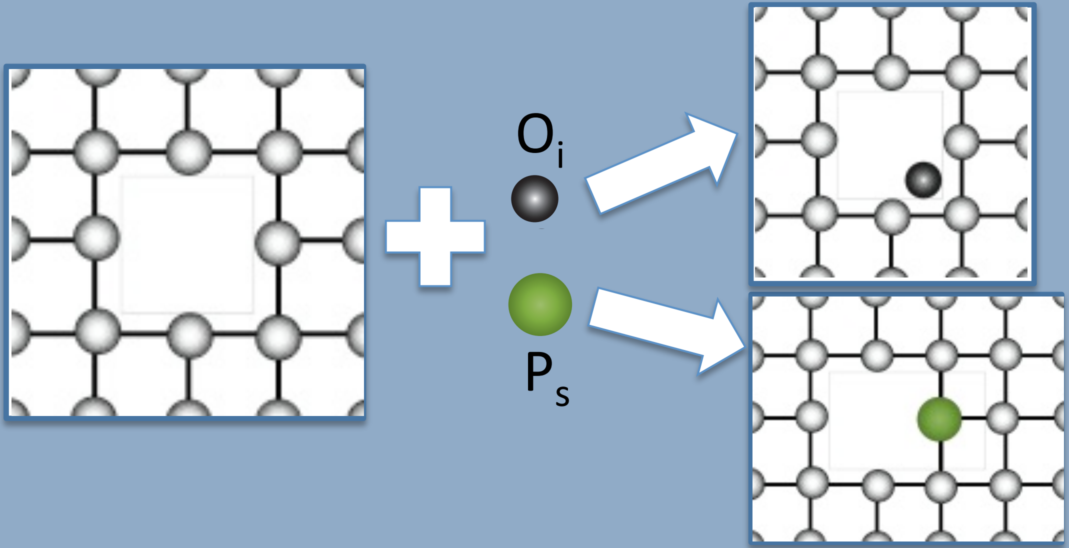
- Frenckel pairs are created due to irradiation
- Defect complexes form due to migration
  - ➔ Migration depends on thermal energy
  - ➔ Kinetics like in chemical reactions

Benefit of oxygen rich silicon: $VO_i$ generation high – VP suppressed

$V+O_i \rightarrow VO_i$

or

$V+P_s \rightarrow VP$



No influence!

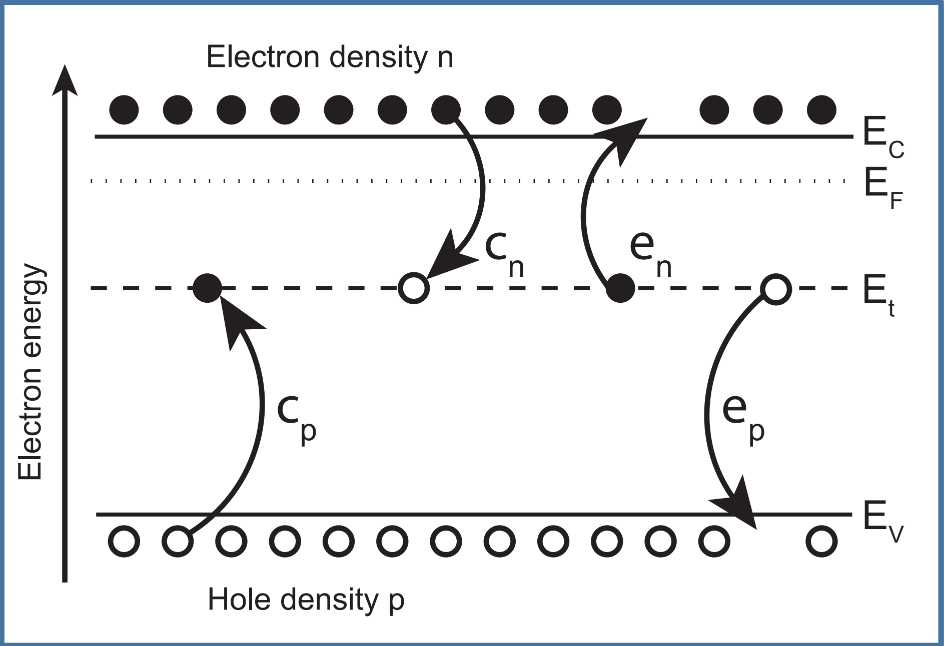
Donor removal

# Defect properties

## Scockley-Read-Hall statistik

Occupancy of defect states with electrons or holes is determined by

capture $c_{n,p} \propto \sigma_{n,p} \cdot n,p$ and emission $e_{n,p} \propto \sigma_{n,p} \cdot \exp\left( \pm \frac{E_t - E_{C,V}}{k_B T} \right)$



### Defect properties

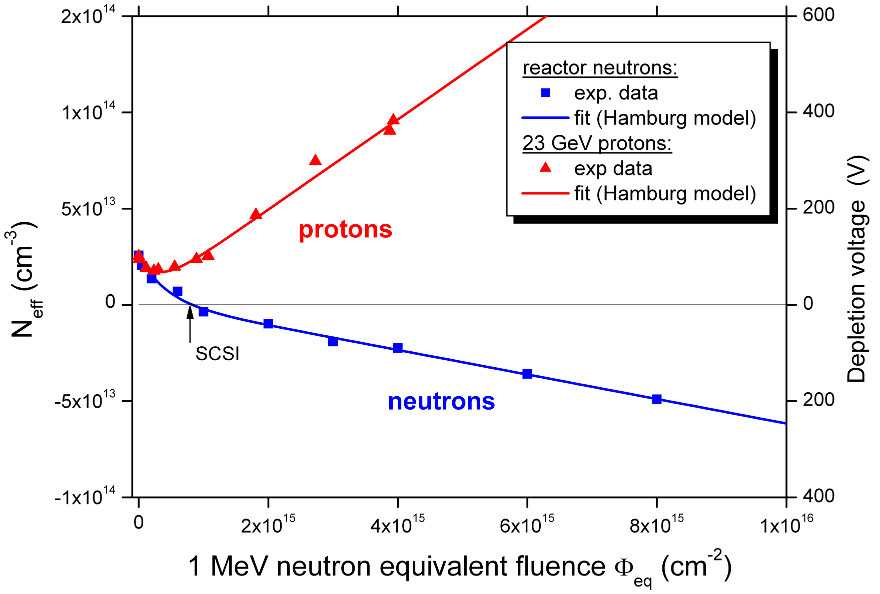
$\sigma_{n,p}$: $e^-$, $h^+$ capture cross section
$E_a$: activation energy for ionisation
$N_t$: trap concentration

Capture of electrons always combined with hole emission and vice versa

De- and recharging offers possibility to detect defects

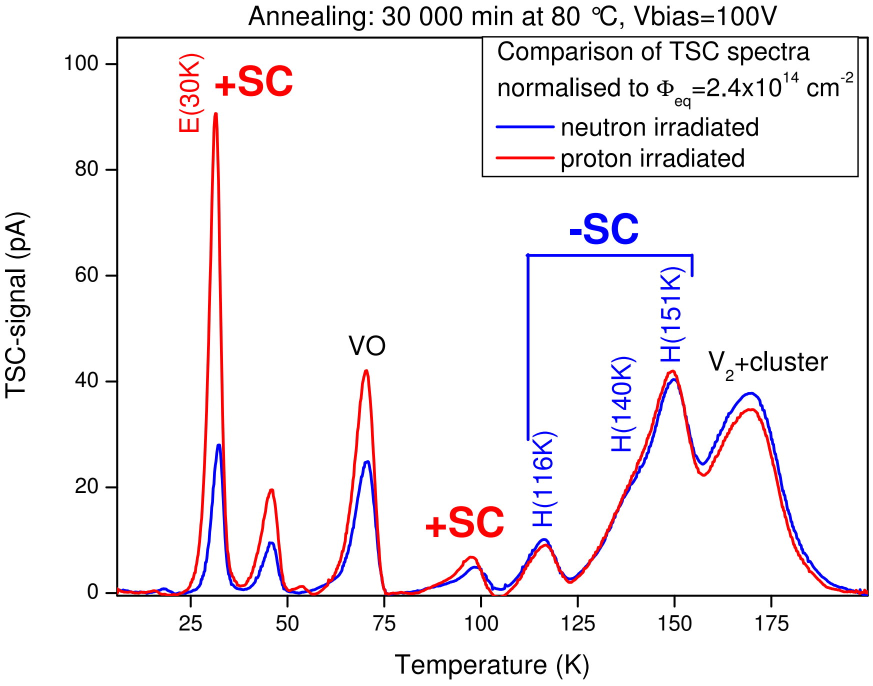
# Defects with impact on $N_{eff}$

## $N_{eff}$ for n and p irradiation (CV) for Epi-Do



I. Pintilie et al. NIM A 611 (2009) 52

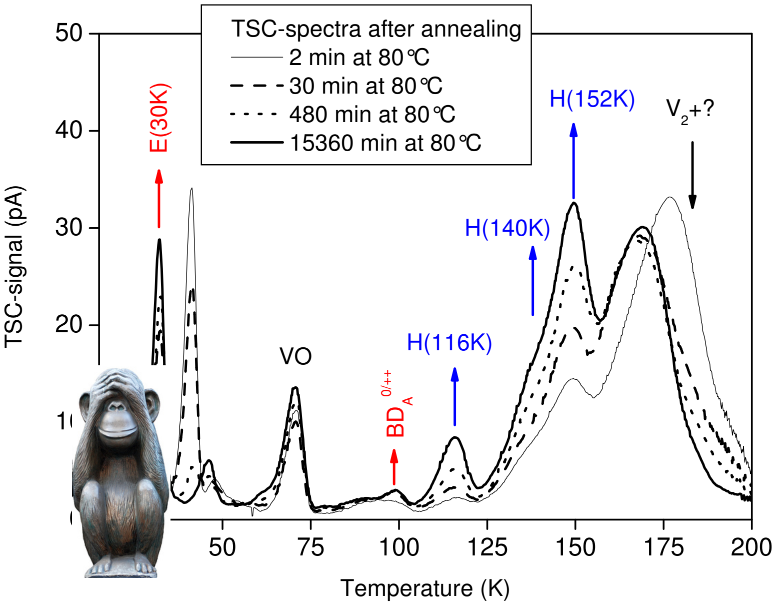
## Corresponding defects (TSC)



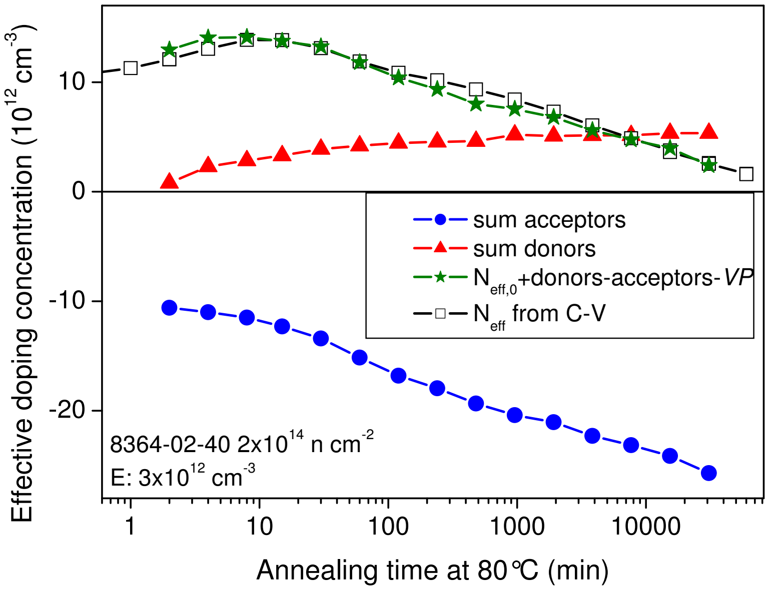
- Cluster defect E(30K) enhanced after protons
- Shallow donor E(30K) overcompensates deep acceptors

# Annealing for Neutron Irradiated Sensors

## $2\text{x}10^{14}$ n $\text{cm}^{-2}$, Epi-St 75 µm (TSC)



## Defect concentrations vs $N_{eff}$ (C-V)

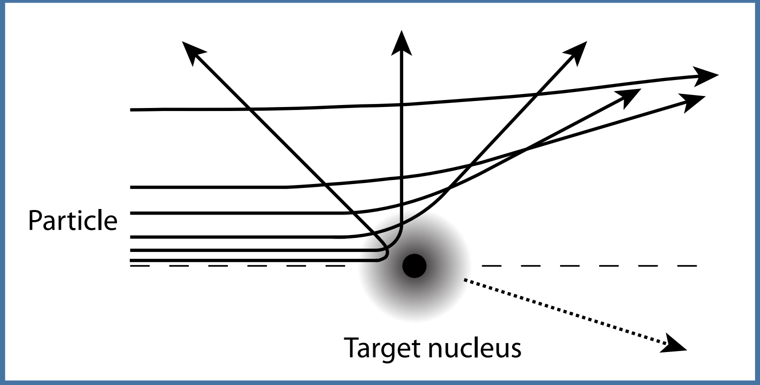


A.Junkes, PhD thesis, Uni Hamburg 2011

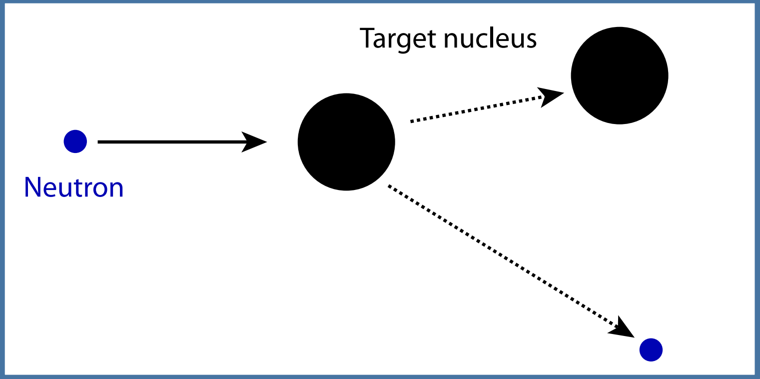
- Concentrations from microscopic measurements reproduce $N_{eff}$ from C-V
- Prediction of $V_{dep}$ possible also for neutron

# Non Ionising Energy Loss → bulk damage

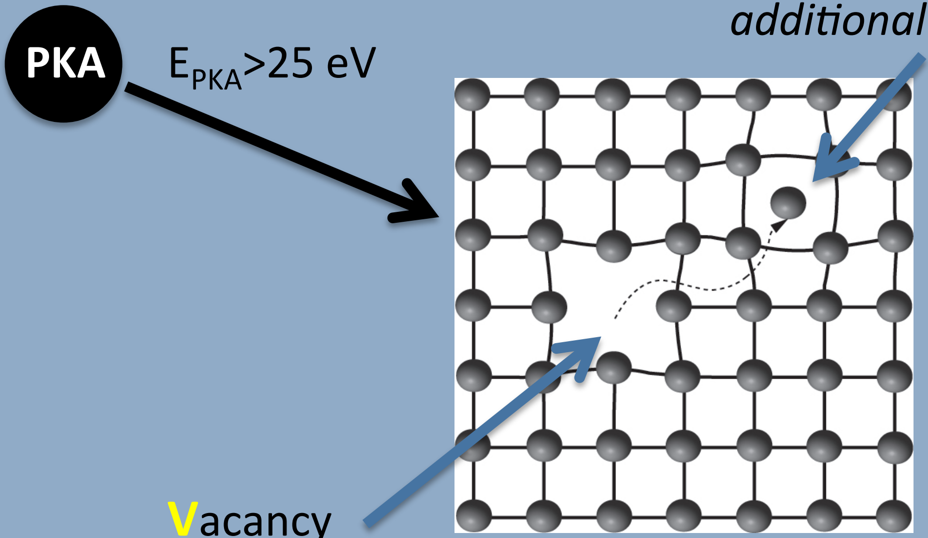
## Coulomb scattering



## Elastic nuclear scattering



| $^{60}$Co-γ | Electrons | Protons | Neutrons |
|---|---|---|---|
| compton electrons | coulomb scattering | coulomb & elastic nuclear scattering | elastic nuclear scattering |



Interstitial
*additional Si atom*

Vacancy
*missing Si atom*